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Route Selection and Environmental Strategies in Subsea Pipeline Engineering

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The Paradigm of Installation-Oriented Planning: A Critical Evaluation of Route Selection and Corridor Planning for the Leupung-Banda Aceh Submarine Clean Water Pipeline

Abstract

The selection of a pipeline route is a critical stage in submarine installation projects that dictates technical success and longterm cost efficiency. This article evaluates the corridor planning for a clean water transmission system from the Leupung mountain springs to the Banda Aceh distribution center, specifically comparing conventional land alignments with submarine alternatives. The study employs a comparative evaluation based on techno-economic criteria, including seabed geology, bathymetry, and natural disaster mitigation specifically addressing the landslide risks prevalent in the Aceh Besar region. The analysis emphasizes that route selection is an "installation-oriented planning" process rather than a mere geometric exercise. By integrating hydrodynamic stability factors and shore approach methods, the research argues that a submarine route utilizing High-Density Polyethylene (HDPE) provides superior resilience against the seismic and geological characteristics of Aceh.

Abdullah Ramadhan[1], Ahmad Asro Septian[2]*, Alexander Poda Siahaan[3], Jonathan Obryan[4], Muh. Fachrul Alfath[5], Obioma Reuben Nwaogbe[6]

[1,2,3,4,5]Department of Ocean Engineering, Hasanuddin University, Indonesia
[6]Nigeria Maritime University, Okerenkoko, Delta State, Nigeria

*Correspondence author:
asroseptian@gmail.com

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1. Introduction

The provision of reliable clean water is a fundamental pillar for the social and economic stability of Banda Aceh City. In the post-tsunami era and amidst rapid urban growth, the city's dependence on local water sources which are increasingly vulnerable to saltwater intrusion poses a serious challenge. One strategic solution involves the transmission of clean water from the mountainous springs of Leupung in Aceh Besar. However, geographical obstacles such as steep hills prone to landslides along the land route necessitate that engineers consider submarine alternatives. This introduction asserts that the success of such a project lies not merely in the piping technology used, but in the most upstream stage: Route Selection. Selecting a route is not just a matter of drawing the shortest line on a map; it is a complex technical process that determines the infrastructure's sustainability against geological and marine hydrodynamic threats [1].

The geographical characteristics of Aceh present unique challenges for linear infrastructure development. The corridor between Leupung and Banda Aceh traverses areas with varying topography, including mountainous terrain, coastal zones, and regions that have experienced significant geomorphological changes following major seismic events. These conditions increase the complexity of pipeline planning because route alternatives must be

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evaluated not only from a construction perspective but also from the standpoint of long-term operational reliability and risk mitigation [2].

In addition to topographical constraints, Aceh is located within a tectonically active region influenced by the interaction of major geological plates. Earthquakes, ground deformation, and coastal changes remain important considerations in infrastructure development throughout the province. Conventional land-based pipeline routes may therefore face challenges related to slope instability and landslide hazards, particularly in areas with steep terrain and high rainfall intensity. Consequently, the resilience of a transmission system against geological disturbances becomes a key criterion in route selection [3].

Recent advances in submarine pipeline engineering have expanded the feasibility of offshore water transmission systems. Improvements in offshore survey technology, installation methods, and pipeline materials have enabled engineers to consider marine corridors that were previously regarded as technically challenging. High-Density Polyethylene (HDPE), in particular, has become increasingly attractive for submarine applications because of its flexibility, corrosion resistance, and ability to accommodate limited seabed movement without experiencing significant structural damage [4].

Against this background, the planning of a clean water transmission system between Leupung and Banda Aceh requires a more comprehensive approach to route evaluation. Rather than focusing solely on distance minimization, route selection should integrate installation feasibility, seabed characteristics, hydrodynamic conditions, and disaster mitigation considerations into a single decision-making framework. Therefore, this article critically evaluates the concept of installation-oriented planning and argues that corridor planning should serve as the foundation for achieving a sustainable and disaster-resilient submarine clean water pipeline system in Aceh.

2. Discussion of Primary Issues

The primary technical issue in planning a submarine pipeline route along the Aceh coast involves the interaction between the pipe material and the dynamic marine environment. Geometrically shortest paths often traverse extreme bathymetric zones or areas with high underwater currents, which technically increases the risk of material fatigue and structural failure. Furthermore, there is the issue of hydrodynamic stability; HDPE pipes, characterized by low density, tend to float and are susceptible to displacement due to wave loads in shallow waters. Without corridor planning based on seabed data, the pipeline installation risks damage from anthropogenic activities, such as ship anchors, or natural phenomena like seabed scouring [5].

Another critical issue is the variability of seabed conditions along the proposed route corridor. Differences in sediment composition, seabed slope, and geological formations can significantly affect installation methods and long-term pipeline performance. Areas with unstable sediments may increase the likelihood of differential settlement or free-span formation, both of which can generate excessive stresses on the pipeline structure. Therefore, route planning must be supported by detailed geotechnical and geophysical investigations to identify potentially problematic sections before construction begins [6].

The shoreline transition zone, commonly referred to as the shore approach, also presents substantial engineering challenges. This area is continuously influenced by wave action, tidal fluctuations, and coastal erosion processes that can threaten pipeline integrity if not properly addressed. In many submarine pipeline projects, the shore approach is considered one of the most vulnerable sections because it experiences the combined effects of marine and terrestrial environmental forces. Consequently, specialized installation techniques such as Horizontal Directional Drilling (HDD) may be required to enhance protection and reduce exposure to coastal hazards [7].

In addition to physical and environmental constraints, operational considerations must also be incorporated into corridor planning. Unlike land-based pipelines, submarine systems are more difficult and costly to inspect, access, and repair once they are in service. A route that appears technically feasible during the design phase may create significant maintenance challenges throughout its operational life. Therefore, route selection should consider not only installation feasibility but also long-term accessibility for inspection, monitoring, and

emergency intervention activities [8].

Furthermore, the Aceh coastal region is characterized by a history of seismic activity and tsunami events, making disaster resilience an essential aspect of infrastructure planning. Pipeline corridors that avoid geologically unstable areas and minimize exposure to potential seabed movement can significantly improve system reliability. As a result, the primary issue in route planning is not merely identifying a feasible alignment, but determining a corridor that balances installation practicality, operational reliability, environmental compatibility, and long-term resilience against natural hazards [9].

3. Review and Critique of Existing Approaches

Conventional literature often prioritizes route selection based on initial Capital Expenditure (CAPEX), where the shortest path is deemed the most efficient. However, this approach tends to overlook long-term Operational Expenditure (OPEX) and the risk of system failure. Many feasibility studies evaluate only a single alignment without performing a deep comparative evaluation of multiple corridor options. A primary critique of current approaches is the lack of integration between real-time bathymetric data and available installation methods. Planning is frequently conducted in isolation from the installation strategy (installation-oriented planning), leading to unforeseen technical constraints during field construction [10].

In the specific context of the Leupung-Banda Aceh corridor, the assumption that the shortest route is the most efficient may lead to misleading conclusions. The mountainous terrain of Aceh Besar presents significant challenges related to slope stability, erosion, and landslide susceptibility. Although a land-based alignment may appear advantageous in terms of distance, additional construction requirements such as excavation works, retaining structures, and slope protection systems can substantially increase overall project costs and technical complexity [11].

Another weakness of existing approaches is the tendency to separate route planning from installation methodology. In many projects, route alternatives are selected before installation techniques are thoroughly evaluated. As a result, alignments that seem feasible during the planning stage may encounter significant difficulties during construction. For submarine pipelines, installation considerations such as pipe flotation control, seabed preparation, and shore approach methods should be incorporated from the beginning of the planning process [12].

Furthermore, conventional feasibility assessments often underestimate the influence of natural hazards on long-term infrastructure performance. Aceh is characterized by active tectonic conditions and a history of major seismic events that have altered both terrestrial and coastal landscapes. Consequently, route selection should incorporate disaster-related risks as a primary evaluation criterion rather than treating them as secondary considerations during later project stages [13].

These limitations indicate that traditional route planning frameworks may not be sufficient for complex coastal infrastructure projects. A more comprehensive evaluation method is required, one that simultaneously considers constructability, environmental conditions, operational reliability, and hazard mitigation. Such an approach forms the basis of installation-oriented planning, where route selection becomes an integrated engineering process rather than a simple geometric optimization exercise.

4. Author's Perspective and Argumentation

The author argues that route selection must adopt an Installation-Oriented Planning approach, where installation feasibility is treated as a primary variable from the earliest stages of project development. In many infrastructure projects, route selection is often performed independently from construction planning, resulting in alignments that appear attractive on paper but become difficult, expensive, or risky to install in practice. For the Leupung–Banda Aceh clean water transmission system, this separation between planning and installation can significantly affect project feasibility due to the challenging geological and coastal conditions of the region. Therefore, route selection should be viewed as an integrated engineering process that simultaneously

considers constructability, operational reliability, and long-term resilience.

The author further emphasizes that the shortest path should not automatically be regarded as the best path. In conventional planning, distance is frequently used as the primary indicator of efficiency because it directly influences material requirements and construction costs. However, in areas characterized by steep terrain and unstable slopes, a shorter alignment may expose the pipeline to greater risks throughout its operational life. A slightly longer route passing through relatively stable terrain or a more favorable marine corridor may ultimately provide better performance by reducing bending stresses, minimizing maintenance requirements, and improving overall system reliability.

Another important argument concerns the suitability of High-Density Polyethylene (HDPE) as the preferred material for the proposed submarine pipeline. The author considers HDPE particularly advantageous for the Aceh region due to its flexibility and resistance to corrosion. Unlike rigid steel pipelines, HDPE is capable of accommodating limited seabed movement and ground deformation without experiencing significant structural damage. Given the seismic characteristics of Aceh and the possibility of future geological disturbances, the flexibility of HDPE provides an additional layer of resilience that supports long-term operational continuity [14].

The author also views corridor planning as a form of infrastructure protection rather than merely a route selection exercise. A well-designed corridor should not only define the pipeline alignment but also establish a protective zone that accounts for environmental loads, installation requirements, and future operational needs. Factors such as minimum bending radius, seabed stability, anchor clearance, and shore approach conditions should be incorporated into corridor development. In particular, the use of shore approach methods such as Horizontal Directional Drilling (HDD) can reduce exposure to coastal erosion and protect critical transition points between terrestrial and marine environments [15].

Based on these considerations, the author maintains that installation-oriented planning offers a more realistic framework for infrastructure development in complex coastal regions. By integrating route selection, installation strategy, material characteristics, and hazard mitigation into a unified planning process, engineers can improve both project feasibility and long-term sustainability. In the specific case of the Leupung–Banda Aceh submarine pipeline, such an approach is expected to provide a safer, more resilient, and more cost-effective solution for ensuring reliable clean water supply in the future.

5. Conclusions

Route selection is a critical stage that determines the fate of the entire submarine pipeline installation system. In the case of the proposed Leupung–Banda Aceh clean water transmission project, route planning should not be viewed merely as a process of identifying the shortest connection between two locations. Instead, it should be considered a comprehensive engineering activity that integrates technical feasibility, installation requirements, environmental conditions, and long-term operational considerations. Failure to properly evaluate these factors during the planning stage may result in increased construction complexity, higher maintenance costs, and reduced infrastructure reliability.

The analysis presented in this article indicates that a submarine route offers significant advantages when compared with conventional land-based alternatives. The geological characteristics of Aceh Besar, including steep terrain and landslide-prone slopes, create substantial risks for terrestrial pipeline systems. By contrast, a carefully selected submarine corridor has the potential to avoid many of these hazards while providing a more stable and sustainable transmission pathway. However, the success of such a solution depends heavily on the quality of route selection and corridor planning conducted during the early stages of project development.

Furthermore, the study highlights the importance of adopting an Installation-Oriented Planning approach. Route selection should be directly linked to installation feasibility, material characteristics, and future maintenance requirements. The use of HDPE pipelines, combined with appropriate ballast systems and suitable shore approach methods, can improve system resilience against the seismic and geological conditions that characterize the Aceh region. In addition, corridor

planning should incorporate sufficient protection measures to reduce exposure to environmental loads and human activities that may threaten pipeline integrity.

Finally, this article argues that future clean water infrastructure projects in coastal and disaster-prone regions should move beyond traditional distance-based optimization methods. A risk-based comparative evaluation that considers geological, hydrodynamic, environmental, and operational factors simultaneously will provide a more reliable basis for decision-making. By placing route selection at the center of project feasibility assessment, planners and engineers can develop submarine pipeline systems that are safer, more efficient, and more resilient in supporting long-term water security for Banda Aceh and surrounding areas.

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